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Abstract

Agriculture is facing up to an increasing number ofchallenges, including the need to ensure variousecosystem services and to resolve apparent conflicts betweenthem. One of the ways forward for agriculture currently being debated is a set of principles grouped together under the umbrella term “ecological intensification”.In published studies, ecological intensification has generally been considered to be based essentially on the use of biological regulation to manage agroecosystems, at field, farm and landscape scales. We propose here five additional avenues that agronomic research could follow to strengthen the ecological intensification of current farming systems. We begin by assuming that progress in plant sciencesover the last two decades provides new insight of potential use toagronomists. Potentially useful new developments in plant science include advances in the fields of energy conversion by plants, nitrogen use efficiency and defence mechanisms against pests. We then suggest that natural ecosystems may also provide sources of inspiration for cropping system design, in terms of theirstructure and function on the onehand, and farmers’ knowledge on the other. Natural ecosystems display a number of interesting properties that could be incorporated into agroecosystems. Wediscuss the value and limitations of attempting to 'mimic' their structure and function, while considering the differences in objectives and constraints between these two types of system. Farmers develop extensive knowledge of the systems they manage. We discuss ways in which this knowledge could be combined with, or fed into scientific knowledge and innovation, and the extent to which this is likely to be possible. The two remaining avenues concern methods. We suggest that agronomists make more use of meta-analysis and comparative system studies,these two types of methods being commonly used in other disciplines but barely usedin agronomy. Meta-analysis would make it possible to quantify variations of cropping system performances in interaction with soil and climate conditions more accurately across environments and socio-economic contexts. Comparative

analysis would help to identify the structural characteristics of cropping and farming systems underlying properties of interest. Such analysis can be performedwith sets of performance indicators andmethods borrowed from ecology for analyses of thestructure and organisation of these systems. These five approaches should make it possible to deepen our knowledge of agroecosystems for action.

1. Introduction

New agricultural systems are required toallow agriculture to satisfy the increasingly diverseexpectations of society. For decades, agronomy has produced knowledge and designed agroecosystems for maximising the production of primary food and fibre, either for direct consumption orfor industrial use. Agricultural production issues have recently been expanded toinclude other ecosystem services (Zhang *et al.*, 2007). Likeother natural and semi-artificial ecosystems, agroecosystems can provide services, such as carbon sequestration, pollination, or water filtration. The capacity of agriculture to providesuch services is, of course, not always guaranteed, and there are manyexamples of adverse effects of agricultural practiceson the environment, leading to ecological disservices of agriculture (Matson *et al.*, 1997; Swinton *et al*., 2007). Disservices may include decreases in water and air quality or a contribution to biodiversity loss. As agroecosystems are ecosystems controlled by humans, adopting the correct approach to a wide range of production issues requires an understanding of the way in which natural and human-driven or forced processes interact within the ecosystem.

Agronomists have argued that the missionsof multi-objective agriculture could best be achieved by making better use of biological regulation mechanisms at different levels: crop management, cropping system design, landscape layout and management (Matson *et al*., 1997; Médiène *et al*., 2011). This assumes that biological mechanisms are able to replace chemical or physical inputs, or to interact favourably with them, playing the same agronomic role without external costs, including environmental costs in particular.The use of biological regulation in agroecosystems to achieve both a high level of food production and to provide ecosystem services, apparently opposite aims,has been placed at the core of what is increasingly called “ecological intensification”. The Food and Agriculture Organisation (FAO, 2009)recently defined “ecological intensification” (or “sustainable intensification”) within the framework of organic agriculture as “Maximization of primary production per unit area without compromising the ability of the system to sustain its productive capacity”. The expression“ecological intensification” was already in usemore than two decades ago (Egger, 1986), when it referred to a kind of ecological engineering in agropastoral systems in Africa, replacing some perennial species to improve soil organic matter content.

A more recent use of the expression by Cassman (1999)focused on cereal production and highlighted the need for progress in plant and soil science to achieve a continuous increase in cereal yields (intensification) without environmental (ecological) damage.This approach focuses principally on the fate of fertilisers and their use by crops. Witt *et al.* (2006) applied a similar approach to oil palm plantations. According toChevassus-au-Louis and Griffon (2008)and a number of other authors (Affholder *et al.*, 2008; Mikolasec *et al*., 2009; Hubert *et al.*, 2010; Bommel *et al.*, 2010),ecological intensification is a pathway towards the production ofmore agricultural product, the production of “new” things (ecosystem services) and different means of production (environmentally friendly). According to Chevassus-au-Louis and Griffon (2008), ecological intensification is basedon “intensification in the use of the natural functionalities that ecosystems offer”. Though relatively vague, this definition remains a possible starting point for the consideration of alternative pathways of development foragriculture. This definition is much broader than that of Cassman (Cassman, 1999), and provides an interestinghaven for scientists promoting the use of biological regulation in agroecosystems.

Many articles have been published on biological regulation in agroecosystems, mostly under the heading "agroecology", and new papers are continuing to appear. Research on this topic remains highly necessary, and is probably a challenge for most agronomists familiar with individualphysical and/or chemical aspects of agroecosystems. However, ecological intensification calls for both a wider diversification of sources of knowledge and the development of new data analysis methods. Agronomists have, until recently, relied essentially on their own scientific output. Prototyping (e.g. Vereijken, 1997; Lançon *et al*., 2007; Debaeke *et al*., 2009) and the model-based design of agricultural systems (e.g. Rossing *et al*., 1997; Bergez *et al*., 2010) are fed by results processed through simulation studies, statistical hypothesis testing and group analysis,from research groups working mostly at experimental stations(Figure 1). We argue here that agronomists would be placed in a better position to tackle ecological intensification if they diversified their sources of knowledge and the methods used to compile, organise and analyse such knowledge. The diversification of knowledge sources may include (i) making use of recent advances in plant sciences, (ii) learning lessons from the functioning of natural ecosystems, guiding the design and management of acroecosystems and (iii) embracing local farmers' knowledge. Methods for assessing these sources of knowledge are necessarily diverse, and couldbe extendedto data mining and the meta-analysis of large datasets containing heterogeneous information and comparative analyses of agroecosystems at different scales. We present here the arguments for further agronomic research in these two related domains: sources of knowledgefor agronomists and data processing methods.

2. Diversifyingsources of knowledge to guide ecological intensification

2.1 – Mobilizingadvances in plant sciences

There has been tremendous progress in plant sciences in recent decades, with detailed elucidation of the genetic and environmental determinism of plant development, growth and reproduction. This progress was made possible, in particular, by increases in our ability todissect cellular and molecular processes, supported by exponential progress in laboratory techniques and the capacity to analyse masses of genomic data (e.g. Tardieu & Tuberosa, 2010). This knowledge about the highly complex life of plants has often been developed in a simplified environment, far removed from the reality of farmers' fields. This has led to a widening of the gap between the research objectives of plant scientists and agronomists.We highlight briefly, with a few examples,ways in which agronomists could make use of advances in plant sciencesto designecologically intensive cropping systems.

<u>2.1.1.A new look at the basics</u>

Agronomists involved in the design and evaluation of cropping systems often make use of a simplified crop description(Monteith 1977),despite the availability of more mechanistic models simulating canopy photosynthesis (Spitters *et al*., 1986; Spitters 1986; Depury & Farquhar, 1997).In this simplified description, the canopy, represented as a "big leaf", intercepts photosynthetically active radiation and converts it to biomass. Branching is generally considered to be the outcome of interplant competition. Mineral nutrition is represented as a simple flux from soil to plant roots, depending on soil mineral and water contents. Such simplified representations have proved sufficient and highly successful for cropping system design. Moreover, the more sophisticated representations of the basic processes of plant life implemented in more complex models do not necessarily improvethe ability of crop models to predict behaviour in a range of fluctuating conditions. Such representations have therefore been used only rarely by agronomists. Nevertheless,results recently obtained in plant sciences suggest that this simple paradigm could be improved, as shown for example by Zhu *et al*. (2010), who analysedthe ways in which improvements in photosynthesis efficiency could contribute to the required increase in yields.

Nutrient use efficiency is alsoclearlya keypoint in ecological intensification. One of the most important issues is decreasing the use of nitrogen fertilisers, to decrease greenhouse gas emissions, to reduce the dependence of agriculture on fossil fuels and to prevent health and environmental disorders, without decreasing productivity (Galloway *et al*., 2008; Spiertz, 2010). Plant scientists have investigated in detail the exchanges of nitrogen between roots and their environment (Jackson *et al*., 2008). Glass (2003) summarised the factors decreasing nitrogen absorption efficiency, on the basis of molecular knowledge and empirical data. Decreases in nitrogen transporter activity and rates of nitrate absorption follow increases in soil ammonium concentration, low temperature and incident radiation. These mechanisms may account, at least in part, for the high variability of fertiliser efficiency observed in field experiments. They also provide us with opportunities to improve nitrogen management in the soil. More generally, the ways in which plants make use of adaptation mechanisms to deal with mineral depletion have been extensively studied on a physiological basis (Grossman & Takahashi, 2001). Agronomists could make use of this work to define the limitswithin which plant environments must be contained to avoid unfavourable plant reactions.

2.1.2. The cultivated plant and its biological environment

Since the middle of the last century, the gradual “artificialisation” of agriculture has led to agronomists paying less attention to the biological components of fields. Agroecology has emerged as a reaction against this excessive simplification of the system, placing the biological component back at the heart of the system (Altieri, 1989), and resulting in the development of an“agroecosystem”view (Conway, 1987). Nevertheless, common agronomic practices still largely ignore biological interactions in cultivated fields, and agroecologists often emphasise the need for an empirical and holistic approach to agroecosystems. New findings in plant sciences concerning the relationships between the plant and its surrounding biotic environment have recently emerged and are of great interest.

Studies of interactions between roots and soil micro-and macro-organisms have revealed the existence of processes of paramount importance for agronomists. Some of these interactions are very familiar to agronomists, including nitrogen fixation by symbiosis between *Rhizobium* sp.and leguminous or non-leguminous(Mehboob *et al*., 2009) plants. Other associations, such as that between other endophytic di-azotrophic bacteria and grasses or cereals, also exist and may be of interest, as pointed out by Reis *et al.* (2000). Plants may be injured by soil pathogenic organisms, but they may also benefit from organisms present in the rhizosphere, through improvements in growth and mineral nutrition, an increase in resistance to unfavourable abiotic conditions, and protection against or an increase in resistance to pathogens (Sturz & Nowak, 2000; Kiers and Denison, 2008).

Whatever the types of organisms considered, the species or plant genotype drives selection of the bacterial community and determines the benefits of plant-rhizosphere mutualism. Improvements in the genomic characterisation of rhizobacterial communities have made it possible to demonstrate that plant genotype influences bacterial assemblages by modifying exudation patterns (Micallef *et al*., 2009). An understanding of the plant genome would make it possible to determine the genetic basis of the mechanism and to make use of genetic variants for the management and manipulation of the rhizosphere community (Ryan *et al*., 2009; Wissuwa *et al*., 2009). These rhizosphere associations and their benefits to the crop also depend strongly on cropping system, so it would seem reasonable to conclude that adapted cropping systems (including crop rotation and crop management measures) could also increase efficiency. The efficacy of the *Rhizobium*/legume association is also highly dependent on cropping system, through the effects of practices on the physical and chemical properties of soils and their water status (Sprent *et al*., 1987). These effects are well known, but should be considered in the light of the recent development of legume nodulation genomics (Stacey *et al*., 2006). Sturz and Nowak (2000) have enlarged their vision to the overall communities of endophytic rhizobacteria with potentially beneficial effects on crop growth through an increase in resistance to unfavourable abiotic conditions and to pathogen aggression, and through improvements in growth and mineral nutrition. The agronomic benefits of these associations with endophytic rhizobacteria depend on the survival of bacterial communities, which in turn depends on soil and crop management (Bowen and Rovira, 1999; Acosta-Martinez *et al*., 2008). One of the ways by which crop management can modulate the evolution of microbial communities,is its effect on root exudates. In addition to altering the physical and chemical properties of the soil, root exudates have been shown to affect both soil micro-organism communities and other eukaryotes (Bertin *et al.*, 2003). Bais *et al.* (2004, 2006) reviewed the nature of the chemicals involved and the corresponding interaction processes for various ecological roles. However, one of the aspects of crop/soil community interactions most frequently ignored by agronomists is probably the role of the common mycorrhizal networks (CMNs), which may be affected directly or indirectly by soil tillage, fertilisers, pesticide use and aerial plant management (Pietikainen & Kytoviita, 2007). The networks that these fungi establish between plants may provide a major route for mineral transfer from plant to plant (He *et al*. 2003). Van der Heijden and Horton (2009) recently reviewed the possibilities for CMN formation between different plant species, their ecological significance and the benefits generated. They found that there were many possibilities for CMN development, but that there were also large differences in the benefits accrued, particularly in terms of promotion of the growth of interconnected plants. Similarly, the role of plant micro-organisms in plant x plant interactions (Sanon *et al*., 2009; Li *et al.*, 2008) and the competition of microbial communities promoting both plant growth and health (Lemanceau *et al*., 2009) illustrate the benefits that agronomists may obtain from advances in research on plant-micro-organism interactions for rhizosphere engineering and management (Ryan *et al*., 2009). Beyond the question of production, Jackson *et al.* (2008), focusing on nitrogen, derived from current knowledge on root/micro-organism interactions the trends in ecosystem services supplied by cropping systems in different agricultural situations. Thanks to the deep insight now available, the contribution of agronomists at system level can be built on mechanistic rather than empirical knowledge, as demonstrated by certain examples in precision agriculture(Welbaum *et al*., 2004).

Interactions between aerial parts of the plant and the surrounding biotic environment have also been described in detail in recent years. The metabolic pathways bywhich plants react both locally and systemically to infection or wounding are increasingly well known (De Bruxelles & Roberts, 2001; Kessler & Baldwin, 2002). Some result in the production of volatile substances, which play a role in herbivore repulsion or plant-to-plant signalling. These findings are promising for genetic engineering approaches, provided that the genetic basis of the metabolic pathways can be identified (Dudareva & Pichersky, 2008). However,cropping system may also play a role, as the expression of the metabolic pathways involved in direct or indirect defence probably depends on interactions between genotype and environment (Le Bot *et al.*, 2009). Moreover, it may be possible to elicit some of these pathways deliberately, with appropriate techniques.

2.1.3. Ways to improve the use of plant sciences for ecological intensification

The preceding two sections do not provide a detailed review of the extensive literature in plant sciences. Instead, they deal with a few examples of recent progress and the possible benefits that agronomists could derive from these advances (see table 1). These examples demonstrate that closer consideration of the results of plant sciences could help agronomists to reach their objectives, paving the way for higher levels of production, better quality products, and less harmful consequences for the environment.Other advances in plant sciences, concerningplant architecture, leaf and root morphogenesis (McSteen & Leyser, 2005; Wang & Li, 2008; Walter *et al.*, 2009),floral biology (e.g. Boss *et al.*, 2004), the role of aquaporins (e.g. Maurel *et al.*, 2008), cell separation processes (Roberts *et al.*, 2002) and long distance signals within plants (Lough & Lucas, 2006), for example, are also of great potential interest to agronomists working on ecological intensification,as they might help crops to avoid or to resist deleterious stresses. However,major efforts are still required to scale-up the results from individual genes, cells or organs to the canopy, and to test the stability of biological results in a wide range of agricultural conditions. It is also important to check that advances in one area are not associated with severe drawbacks in others. However, these findings are nonetheless precious to agronomists, who will need to use all the means available to construct novel, more resource-use efficient and/or productivecropping systems.

Finally, there are many different drivers of change in ecological intensification (see introduction and subsequent sections). Innovative systems that have already been developed in the domain of ecological intensification, such as the use of mixtures of cultivars or species, agroforestry andno-tillage systems, would certainly benefit from the knowledge provided by plant sciences. However, these systems will themselves raise new questions and issue new challenges to plant science. For example, although progress has been made in this area, plant sciences results are still often obtained in highlysimplified systems and therefore cannot easily be translated to multispecies systems. Above-ground competition for light and below-ground competition for water are major processes inecological intensification that require study in systems including facilitation between plants (Long & Nair, 1999;Zhang *et al*., 2008; Malézieux *et al*., 2009).

2.2 - Learninglessons from the functioning of natural ecosystems

Strategies for agroecosystem design and management may be derived from the observation of natural ecosystems, guiding alternative agronomic practices (Malézieux, 2011). Several authors (e.g. Ewel, 1999; Altieri, 2002; Jackson, 2002; Vandermeer, 2003) have already suggested that natural ecosystems may provide appropriate models for agroecosystem design to achieve both environmental and social goals while ensuring long-term sustainability. This idea is basedon the assumption that natural ecosystems are adapted to local constraints, due to a long process of natural selection (Dawson & Fry, 1998; Ewel, 1999). It is therefore assumed that the incorporation of certain characteristics of natural ecosystems into agroecosystems would improve some of the properties of agroecosystems, such as productivity (Fukai, 1993), stability (Aerts, 1999; Schulte *et al*., 2002) and resilience (Lefroy *et al*., 1999). These features are particularly useful for dealing with pest outbreaks (Trenbath, 1993) and increasing energy efficiency in a context of the depletion of fossil fuels (Hatfield, 1997). A similar reasoning was followed in the framework of Ecoagriculture, proposed by McNeely andScherr (2003), which places biodiversity at the heart of strategies to conserve and restore ecosystem services, increase wild populations in agroecosystems, and sustain agricultural production. An illustration of this mimicry is providedfor cropping systems in Figure 2 with an emphasis on crop protection. In natural ecosystems, the various animal and plant species interact through population dynamics and trophic networks, providing the final ecosystem with services, such as pollination. In standard cropping systems, these interactions may lead to pest damage on crops, which may be managed with various control methods to limit yield loss. An increase in plant species diversity in systems mimicking natural ecosystems could allow natural enemies to control pests and generate ecosystem services.

2.2.1 What does “Mimicking natural ecosystems” mean?

There have been only a few practical attempts to design agroecosystems from nature. Jackson and Jackson (1999) aimed to develop sustainable cropping systems by mimicking the mid-grass American prairie, creating crop mixtures analogous to the vegetationstructure of the prairie. Traditional agroecosystems in the tropics, long unknown or disparaged by some agronomists, are frequently based on the integrated management of local natural resources and, in many cases, on the management of local biodiversity. These systems may also be considered to result from the observation of nearby natural ecosystems by generations of farmers, who have aimed to mimic the functioning and structure of these natural systems. For example, slash and burn systems can be considered to mimic nature behaviour after fire. Agroforestry systems in the humid tropics mimic the structure and functioning of rainforests. According to Ewel (1999), humid tropical ecosystems appear to be particularly suitable for application of the "mimicry of Nature" concept. Agroforestry systems in the humid tropics are based on the tropical rainforest model. They combine several strata, have a high level of species diversity and are very widespread in Asia, Oceania, Africa and Latin America. Such systemsprovideboth subsistence for local populations and major environmental and socio-economic services (Sanchez, 1995; Nair, 2001). Lying halfway between agro- and forest ecosystems, agroforestry systems combine annual and perennial, herbaceous and woody species, in a more or less complex whole in terms of the number of plant species and practices (Torquebiau, 2007). The damar agroforests of Sumatra, or the cocoa-based agroforests of

Cameroon or Costa Rica, are original ways in which farming communities use natural resources in human reconstructions of both "natural" and productive ecosystems from natural ecosystems (Michon *et al*., 1995, 2007; Schroth *et al*., 2001, 2004).

The scientific foundations of the mimicry paradigm, however, remain to be studied thoroughly (Malézieux, 2011). The potential of this approach to generate innovative agroecosystems in practice also remains largely unknown. Ewel (1999) and Van Noordwijck and Ong (1999) proposed two principles for the design of agroecosystems based onnatural ecosystem mimicry. According to the first of these principles, agroecosystems should mimic the structure and function of natural ecosystems existing in a given pedoclimatic zone. According to the second, agroecosystems should also mimic the diversity of species existing in natural ecosystems, thereby maintaining the diversity of natural ecosystems in the given zone. The first of these principles is clear enough, but must be extended to be effective. Indeed, there are many functions, and structure can be assessed at different scales. Furthermore, basing agroecosytem design solely on natural ecosystems present in the same area may be too limiting: some good ideas might emerge from the study of very distant systems.

According to the second principle, the redesign of agroecosystems inmore ecologically intensive configurations implies their diversification. This has been the case, for example, in Cuba, where small- and medium-scale farmers have tended to diversify their production systems in response to their limited access to or total lack of agricultural inputs to sustain productivity (Funez-Monzote *et al.*, 2009).The resulting diversified systems areenergetically more efficient, less dependent on external inputs, more productive, adaptable and resilient. The diversification of agroecosystems within the mimicry paradigm may be achieved by increasing the number of microorganisms, plant and animal species relevant to agriculture overspace and time, or through agrobiodiversity, a subset of general biodiversity (Brookfield *et al*., 2003). However, natural ecosystem mimicry cannot mean reproducing the diversity observed in natural ecosystems, for at least three reasons. First, recent reviews of existing knowledge in ecology have demonstrated that functional composition controls ecosystem functioning more frequently than species diversity (Hooper *et al*., 2005). As our purpose is to improve agroecosystem functioning through ecological intensification, and not to conserve natural species biodiversity *per se* within agroecosystems, agronomists should concentrate on identification of the level of functional biodiversity resulting in the expression of interesting properties. As pointed outby Main (1999), who addressed the question of how much biodiversity is enough in the context of agroecosystems mimicking nature, the level of diversity considered adequate strongly depends on the goals and criteria used forevaluation. Moreover, interesting properties may arise from the spatial and temporal organisation of the species rather than purely from their number. For example, lessons can be learnedfrom studies of natural ecosystems addressing agronomic topics: nutrient cycling within a complex landscapemay be useful for optimising nutrient management in areas worked by humans, community ecology in natural ecosystems may facilitate the design of new crop protection strategies and an understanding of facilitation within natural ecosystems should make it easier to make use ofthis process in agroecosystems. Finally, approaches based on mimicking natural ecosystems will inevitably be confronted with the “aim problem”. Natural ecosystems provide many services but are not targeted. Agroecosystems, by contrast, are designed to optimise different aspects and toachieve different goals. Consequently approaches mimicking natural ecosystems are limited by certainagricultural obligations, such as the removal of the minerals contained in agricultural products. Some insight may be gained from regarding agroecosystems as complex systems with many simultaneous feedback loops including a dimension absent from natural ecosystems: human agency.

2.2.2 Agroecosystems as complex socio-ecological systems

Agroecosystems are systems that combine sociological and ecological dynamics, in interaction.In complex, dynamic and spatially heterogeneous systems, interactions take place over scales generating emergent properties and self-regulatory mechanisms (Holling, 1973). These mechanisms often manifest as cross-scale feedback, or *panarchy* (Gunderson *et al.*, 2002), and societies contribute to system regulation through adaptive management. For example, in smallholder agricultural systems making use of communally shared resources, buffering and regulatory mechanisms often emerge from collective action (Meinzen-Dick *et al*., 2004). This is why agroecosystems may be defined as socio-ecological systems, or cybernetic systems steered by humans to attain certain goals (see Conway, 1987). The capacity of farmers to adapt plays a major role in system resilience and, byanalogy to the concept of informal economies (de Soto, 2000), regulatory mechanisms operate as informal resource flows that are often unaccounted for in agroecosystems analysis (Tittonell *et al*., 2009). Just as natural ecosystems have a“memory”as a direct consequence of their history, so do agroecosystems, except that some of that memory lies in human agency (Tittonell, 2007).

A wider definition of agroecosystem diversification, more compatible with the socio-ecological nature of complex agroecosystems, must consider not only species diversity, but also the diversity of agricultural practices and rural knowledge adapted to/derived from local pedoclimatic conditions. These lie at the core of human agency and represent new sources of knowledge for agronomic research (see below). Agroecosystem diversification in its broadestsense thus concerns the diversity of livelihood strategies ata certain location, diverse land use, management and marketing strategies, the integration of production activities (e.g. crop-livestock interactions), spatial and temporal associations of crops and crop cultivars, and the maintenance of genetic agrobiodiversity in the system. The efficiency of use of natural, economic and social resources in agroecosystems —which goes beyond the partial use efficiency of a certain single input —and desirable properties, such as stability and resilience,are based on one or more of these categories of diversity. New avenues for agronomy to strengthen agroecological intensification should go beyond the cultivated field or the mixture of species in a given landscape. They should explore desirable properties and mechanisms that operate at the scale of complex socio-ecological systems *i.e.*that take into account sociological and ecological dynamics and interactions in agroecosystems.

2.3 - Farmers' knowledge and lay expertisevalorisation and integration into scientific knowledge

Farmers do not rely exclusively on the results and output of agronomic research to operate their agroecosystems.They make use ofmuch wider knowledge, based on their own experiences and on exchanges with other farmers and advisers, thus building their own expertise. This expertise is rooted in the need to act whatever the level ofagronomic knowledge available: sound and detailed or unreliable and patchy. It is also dependent on the characteristics (environmental, economic, social) of the situation in which it is constructed. According toPrior (2003), we may consider farmers to be*lay experts* (although this denomination entails an antinomy): *experts* because of their experience-basedknowledge and*lay* because this knowledge is limited in scope and doesnot give farmersthe broader and deductive understanding characteristic of scientific or expert knowledge. Recognition of the value of lay expertise is both a necessity and a challenge in many domains, such as medicine (*e.g.* adapting treatments according to the patient's reactions, both as observed by doctors and as interpreted by the patient) and industry (particularlyfor fault detection in plant or machine operation). However, although the value of this lay expertise is recognized, it is not used to build or extend the current scientific knowledge, but to adapt its application in local situations (Henderson, 2010).

Farmers can observe not only their own production systems, but also other systems (both agricultural and natural) and interactions between these systems. They can also gainexperimental knowledge in their own systems. They are often willing to do so and therefore carry out experiments in the operation of their own agroecosystem, evaluating the response of the system to their decisions. This generates different types of knowledge. When confronted with, observing or learning from natural ecosystems, farmers gain knowledge similar to what is generally referred to as *local* or *traditional ecological knowledge* (LEK or TEK, Berkes, 1999). Over generations, they may also build traditional knowledge (not specifically ecological), refined by years of adaptation (see previous section). When experimenting, they build a mixture of experience-basedand experimental knowledge. Many studies have considered the use of LEK/TEK, but most have focused on the use of this knowledge for natural resource management (including fisheries and forestry systems,which more closely resemble a subsistence harvesting activity) rather than the design or improvement of productive agricultural systems. Fewer studies have directly investigated farmers' knowledge. The studies that have been carried out in this domain have mostly assessed the validity of this knowledge (e.g.Grossman, 2003; Friedman *et al.*, 2007; Grace *et al*, 2009) or considered the local adaptation of more generic solutions (e.g. Steiner, 1998, Affholder *et al.,* 2010). However, farmers' knowledge is not only of value for application and for the adaptation of agronomic knowledge to a particular case. It can also be used to extend the available scientific agronomic knowledge (see the examples presented in Table 2). We will defend this point and discuss the various issues it raises below.

2.3.1. Value of farmers' knowledge for agronomy

We will analyse separately the lay expertise (resulting from farmers' activities and interactions with their own systems) and the more traditional knowledge that some farmers or societies have developedover time. The value of lay expertise for agronomy and for development (support to farmers) has been recognised for some time (e.g. Barzman *et al.*, 1996; Baars & de Vries, 1999). This lay expertise can helpto enlargecurrent agronomic knowledge in variousways. First, farmers operate their agroecosystem even in the absence of appropriate knowledge, because they have to. They therefore develop experience-based knowledge that can fill in some of the gaps in scientific knowledge. However, as mentioned above, this experience-based knowledge is often limited to the farmer's own particular case, whereas scientific knowledge should be more general.

Second, some traditional practices are based on the observation of natural ecosystems (Chalmers & Fabricius, 2007; Reed *et al.*, 2007), which, as we have seen, may be of value forecological intensification. Chalmers & Fabricius (2007), for example, showed that local experts, using their ecological knowledge, were able to put forward explanations for changes intheir system, some of which were also provided by scientific knowledge. However,the local experts also had other explanations rooted in a more generalunderstanding of the system. Traditional farming systems can also be a source of understanding and inspiration for the design of sustainable farming systems. Singh & Sureja (2008) showed, for example, how traditional farming systems cope with harsh environments through the management of a wide diversity of plants providing genetic resources. Abbona *et al.* (2007) evaluated the sustainability of a traditional vineyard system in Argentina, both in its original location and in a newly planted area. They showed that the traditional system, in its original location, wasindeed sustainable, whereas this system was not sustainable in its new, different location. They concluded that the efficacy of the traditional system was dependent on the location in which and for which it had been developed over time. During this evaluation process, based on the use of indicators developed for this analysis through the adaptation of existing methods, these authors gained insight into and an understanding of the ecological processes at work in the traditional vineyard system. The analysis of traditional farmers' practices therefore provided an opportunity to obtain new scientific knowledge. In a different context, Ballard *et al*. (2008) analysed the knowledge involved in the management and monitoring activities of community-based forestry groups and the ways in which local and scientific knowledge complemented each other. They showed that local knowledge provided a rapid and efficient means of assessing the effects of management practices on the forest. The same was found forgreenhouse tomatomanagement. Tchamitchian *et al*. (2006) successfully used the concept of"crop vigour" as an indicator in their expert system controlling the daily greenhouse climate for tomato production. Tomato cropvigour is readily assessed by growers of greenhouse tomato crops, on the basis of a set of observations: plant tip colour and shape, fruit load on the crop, crop overall colour. Scientists relate these observations to the generative to vegetative balance of the crop and its ability to perform photosynthesis(Navarrete *et al*. 1997), without being able to model it formally.

Taken as a whole, local knowledge and lay expertise can provide clues to the natural or ecological processes most useful in the design of sustainable farming systems, such as the natural regulation of pest populations by their predators (Barzman *et al*., 1996; Sinzogan *et al*. 2004), or management of the soil and its mineral balance (Steiner, 1998; Okoba & de Graaf, 2005; Saito *et al.*, 2006; Abbona *et al.*, 2007). They can also be of value in the design of assessment methods or indicators for monitoring the ecological performances of these farming systems.

2.3.2 Qualification and validation of lay expertise and knowledge expression

Although both interesting and challenging, the lay expertise of farmers (or advisers) is not easy to use. First, this lay expertise must be elicited and represented. Several methodologies have been proposed for expert knowledge elicitation, either for specific applications, such as plant disease epidemics (Hughes & Madden, 2002), or for more general applications (Cornelissen *et al.*, 2003; Ley *et al.*, 2010). Appropriate elicitation methods include the selection of apanel of experts and the associated delimitation of the knowledge domain considered. The choice of representation also influences the elicitation process. Many authors advocate the use of fuzzy models, which allow the use of linguistic terms and are more suitable for the expression of knowledge in qualitative rather than quantitative terms. By contrast, scientific knowledge is most frequently modelled in quantitative terms, particularlywhen the goal is to represent the operation of a system under the influence of both controlled (human decisions and actions) and uncontrolled (environment) factors. Most of the agronomic models built to simulate agroecosystems are numerical models in which thevariables have point values rather than interval or probabilistic values. There is therefore a gap between the most common representation of scientific knowledge and that of lay expertise, hindering the combination and merging of these two types of knowledge. However, differences in representation are not the only difficulty. As pointed outby Prior (2003), lay experts maybe wrong, either because of the limited scope of their experience or because their conclusions are based on false premises (misobservations, for example, due to a lack of knowledge or skills). Their knowledge is also situation-dependent in that it is obtained in a domain of low variability (one of the goals of agricultural practices is often to reduce variability and diversity in agroecosystems,a goal challenged byecological intensification). Lay expertise should therefore be qualified and analysed independently, in several different ways: domain of validity, certainty and precision. The domain of validity is important because knowledge should be associated witha description of the domain in which it was obtained (rangesof the variables considered, for example); this factor can be used to analyse the extent to which the knowledge obtained is generic. Certainty refers to the confidence that can be attributedto the knowledge. Finally, precision measures how close to a numerical expression it is possible to get in the expression of the knowledge. Even certain knowledge may display a low precision rendering its use purely hypothetical (ventilating a greenhouse does modify its temperature, but the change is difficult to indicate with precision). Artificial intelligence provides a framework for representing expertise and analysing the conflicts arising when information from different sources is compared (several lay experts or a combination of lay expertise and scientific knowledge; Amgoud & Kaci, 2007; Bench-Capon & Dunne, 2007; Alsinet *et al*. 2008; Amgoud & Prade, 2009). However, this domain (qualitative reasoning and argumentation) is still developing and, to our knowledge, its concepts and tools have not yet been used to merge lay expertise and scientific knowledge in agronomy (there are applications for database fusion, assisting debate preparation and industrial planning). The added value of these approaches lies in the need to providean explanation detailing the arguments supporting a piece of knowledge, therefore addressing the questions of certainty and precisionraised above.

The qualification of lay expertise has been shown to be a necessary step in approaches aiming to combine this expertisewith scientific knowledge. Going beyond the issues of the domain of validity, certainty and precision, there is the question of validation of the new knowledge obtained. However, classical validation procedures cannot readily be applied, because the observations underlying the experience-based knowledge acquired are lacking. For example, to validate the greenhouse management rules formalised from expert knowledge, Tchamitchian *et al*. (2006) used a two-step method rather than a direct validation of the rules themselves, which was not possible. The first step involved checking that the application of these rules really did result in the desired pattern of behaviour in the greenhouse (as expressed when building the rules), without questioning the agronomic validity of this behaviour. The second step involvedassessingthe quality of production obtained by applying these rules, the goal being to obtain appropriate production levels from the greenhouse. Attempts at the direct validation of a given rule have only made explicit which pieces of agronomic knowledge can be used to support a given rule. However,it would not have been possible to designthe rule from this identified scientific knowledge, generally because the scopes of the scientific knowledge and that of the lay expertise yielding the rule were different.

3. Methods for synthesizing information

The three main research methods currently used by agronomists (figure 1)are varioustypes of field experiments, on-farm inquiries (e.g. Doré *et al*., 2008), and modelling (e.g. Rossing *et al*., 1997; Bergez *et al*., 2010). Field experiments provide validated knowledge meeting the scientific rules for data acquisition. This basic knowledge can be supplemented by inquiries providing data from real-world agricultural situations (farms). Modelling can be used to explore the response of key agronomic and environmental variables, such as,for example,yield or nitrogen loss, to climate, cropping system variables or societal changes. Thedata generated are then processed, mostly byclassical methods,such as simulation studies, single-experiment data analysis, or group analysis.These methods could probably be complemented with two other methods: meta-analysis, involving the statistical synthesis of results from a series of studies, and comparative analyses of agroecosystems, involving the use of large-scale comparisons similar to those used in ecology (*e.g.* Fortunel *et al*., 2009).

3.1. Meta-analysis and agronomy

Meta-analysis (e.g., Borenstein *et al*., 2009)is more powerful than a simple narrative review of a series of studies, because it synthesises published data in a quantitative manner and makes it possible to assess thebetween-study variability of a variable of interest.

Both scientific researchers and decision-makers can benefit from meta-analysis in several ways (Sutton *et al*., 2000), as this approachprovides a methodological framework for (i) exploringwhat has already been done on a given research topic and identifying more clearly where the gaps and uncertaintieslie,(ii)generating an overview ofdivergent results, (iii) guidingdecisions based on a systematic review and statistical analysis of all the available data related to a given topic, (iv) broadening the knowledge base and allowing replication for the testing of hypotheses, (v) adding to the cumulative development of science.

Most meta-analyses carried out to date have been performed in medical science (Normand, 1999; Sutton *et al*., 2000). This approach has been less systematically applied in other areas of research, such as ecology (e.g., Arnqvist & Wooster, 1995; Cardinale*et al.*, 2006), and has sometimes been applied inagriculture (e.g. Bengtsson *et al*., 2005), animal science (Sauvant *et al*. 2008) and plant pathology (Rosenberg *et al.*, 2004). In agronomy, meta-analysis methods have generally been used to compare the effects of different cropping techniques or of different cropping systems on yield or biomass production. For example, Miguez & Bollero (2005) used a meta-analysis method to summarise and describequantitatively the effect of several winter cover crops on maize yield. The authors estimated the ratio of maize yield after a winter cover crop to maize yield with no cover from 37 published studies carried out in various regions of the USA and Canada. In another study, Miguez *et al*. (2008) studied the effects of planting density and nitrogen fertiliser on the biomass production of *Miscanthus x giganteus*, using 31 published studies including biomass measurements at different dates overseveral years. Drawing on published studies on sub-Saharan African agriculture, Chikowo *et al.* (2010) conducted a meta-analysis of factors controlling nitrogen and phosphorus capture and conversion efficiencies by major cereal crops. The meta-analysis carried out by Badgley *et al.* (2007) did not focus on a specific cropping technique, but was performed to compare two agricultural systems: organic *versus* conventional or low-intensity. The authors compared the yields obtained in an organic system with those obtained in conventional or low-intensity food production systems, based on yield data from293 individual studies on various crops. These data were used to estimate the meanyield ratio for variousfood categories, for both developed and developing countries.

Diverse techniques for meta-analysis are available (e.g., Borenstein *et al*. 2009; Sutton *et al*., 2000), but meta-analysis should always include the following steps:

i. Definition of the objective of the meta-analysis and of the variable of interest to be estimated from the data (e.g., in Miguez and Bollero 2005, the variable of interest is the ratio of maize yield after a winter cover crop to maize yield in the absence of a cover crop).

ii. Systematic review of the literature and/or of the dataset reporting values of the quantities of interest.

iii. Analysis of data quality (i.e., quality of the experimental designs and of the measurement techniques).

iv. Assessment of between-study variability and heterogeneity. Evaluation of the between-study variability of the variable of interest and of the heterogeneity of the accuracy of individual estimates is an important step in a meta-analysis and several statistical methods have been proposed to estimate between- and within-study variances (Borenstein *et al*., 2009). Combination of the individual study estimates and estimation of a mean value for the variable of interest, for example, can be achieved by calculating a weighted sum of individual estimates derived from the studies collected in step ii.

v. Assessment of publication bias. Publication bias occurs when only studies with highly significant results are published. In this case, a meta-analysis can lead to a biased conclusion and overestimation of the effect of a given factor. The 'funnel plot' technique can be used to deal with this issue (e.g., Borenstein *et al*., 2009).

vi. Presentation of the results and of the level of uncertainty.

In the context of ecological intensification, the meta-analysis framework constitutes an interesting alternative to dynamic crop models. Dynamic crop models can be used both to assess the consequences of cropping techniques and environmental variables forcrop production (e.g., Jones & Thornton, 2003) and to assess the effect of cropping systems on keyenvironmental variables (e.g., Rolland *et al*., 2008), two key issues for ecological intensification. However,these models include several sources of uncertainty (Monod *et al*., 2006) and their predictions are not always reliable (e.g., Barbottin *et al*., 2008; Makowski *et al*., 2009). We believe that meta-analysis should be more systematically used by agronomists, to assess and compare the effects of cropping systems on productivity, risks of soil and water pollution, greenhouse gas emissions and biodiversity. A considerable body of experimental data is available for such purposes (e.g., Rochette & Janzen, 2005). Such data could be reviewed, combinedand analysed withstatistical techniques, to rank cropping systems as a function of their impact on key environmental variables, such as water nitrate content, greenhouse gas emissions (e.g., N_2O) and the presence/absence of species of ecological interest (e.g., earthworms, birds). However, meta-analysis requires the use of appropriate techniques and the value of a meta-analysis may be greatly decreased if the six steps outlined above are not rigorously implemented.

3.2. Comparative analysis of agroecosystems

Informationuseful for the ecological intensification of agroecosystems may be obtainedfrom comparative analyses of the structural and functional properties and performance of contrasting agroecosystems. Similar approaches, based on temporal or spatial comparisons, are used in other fields of research, such as plant sciences (Wright *et al.,* 2004; Vile *et al*., 2005; Mauseth, 2006), evolution sciences (Schluessel *et al*., 2008) and marine ecology (Fuhrman & Steele, 2008). The comparative analysis of agroecosystems andcomparisons of agroecosystems with natural ecosystems involve the simultaneous analysis of multiple criteria, with evaluation of the extent to which theydisplayspecific system properties. Several approaches have been proposed for this purpose (e.g., Pannel and Glenn, 2000; de Bie, 2000; Xu and Mage, 2001; Lopez-Ridaura *et al*., 2002; Giampietro, 2003), based largely on concepts formulated more than a decade ago, by authors such as Conway (1987) andMartern (1988). These methods evaluateindicators relatingto the properties of agroecosystems, such as productivity, stability and resilience. These properties are often interdependent and, as pointed out by Marten (1988), they are not universal and must be redefined under each new set of conditions. As discussed above, studies of the local knowledge sustaining various mechanisms of indigenous resilience across contrasting agroecosystems, particularly at the scale of the landscape and its functionality (e.g., Birman *et al.*, 2010), are also a promising starting point for obtaining information useful for ecological intensification. In the next few paragraphs, we examine briefly some critical issues relating to the choice of indicators in multicriteria evaluations (3.2.1) and identify innovative ways of looking at the relationship between structure and function in agroecosystems.

3.2.1 Comparative analysis based on multiple indicators

In practice, the implementation of multicriteria analytical frameworks often involves the selection of a number of indicators (or the use of a list of predetermined indicators) and of reference threshold values for each indicator. The selection of indicators is frequently biased towards the disciplinary standpoint of the observer or highly influenced by certain stakeholders, so ‘quality control’ methods for evaluating the choice of indicators are necessary. In their examination ofthe choice of indicators in different case studies, Groot and Pacini (2010) argued that multicriteria evaluations should involve the analysis of four main system properties: performance, diversity, coherence and connectedness, which can be approached from four dimensions: physical, ecological, productive and social. Performance relates to functional properties of the agroecosystem, such as capacity, stability and resilience. Diversity relates to the structural properties sustaining such functions. Indicators of coherence describe the degree of interaction between components or subsystems within an agroecosystem, andconnectedness describes interactions with adjacent systems (i.e., other agroecosystems, urban or natural systems, etc.). When several indicators are considered simultaneously, it may be pertinent to check whether all the relevant criteria pertaining to system performance, diversity, coherence or connectedness are given equal importance. For example, López-Ridaura *et al*. (2002) and Pacini *et al.*(2003) used two sets of indicators in two independent evaluations of agroecosystems. Although both methods considered multiple criteria pertaining to system sustainability, they weighted thevarious system properties and/or dimensions of sustainability differently.

In general, comparative analyses based on indicators providea static picture of the status of agroecosystems at one particular point in time, without considering the underlying feedback and system dynamics responsible for bringing the system to its current status and for any subsequent change to that status. Beyond comparing multiple indicators and the tradeoffs between them, the comparative analysis of agroecosystems should aim to distil the relationships between relevant properties; e.g., between performance on the one hand, and diversity, coherence and connectedness on the other. A common denominator ofthe indicators used in multi-criteria evaluations is their interdependence and their dependence on the structural diversity of the agroecosystem. Thisinterdependence results from the co-adaptation of agroecosystem components over time. The structural diversity ofagroecosystems,corresponding to the diversity of system components and their interrelationships, is only functional when organised in a specific way.

3.2.2 Analysing the structure and functioning of agroecosystems

It is often postulated that the ecological intensification of agroecosystems may be achieved through gradual diversification to capitalise on regulatory principles and mechanisms inherent to natural ecosystems (see above and, for example, Altieri, 1999; Gliessman, 2001; Wezel *et al.,* 2009). Knowledge of the structural diversity of an agroecosystem, however, may not be sufficient to explain its behaviour, and the way in which the diverse components of the system relate to each other should also be known. Moreover, unnecessarily high degrees ofdiversity of system components and flows within systems with poorly organised configurations may lead to redundancy (Kauffman, 1995; Ulanowicz, 2004). Here, we examine some methods for studying the diversity and organisation of system components based on the theory of networks that may be used in the comparative analysis of agroecosystems.

Indicators of networkcomplexity and organisation have beenderived from communication science. They were first used in economics by Leontief (1951, 1966), and later introduced into ecology by Hannon (1973). Indicators, such as average mutual information (AMI) and ascendency (A), were proposed by Ulanowicz (1997, 2004) for characterisation of the development capacity (in terms of increased organisation) of ecological systems, and have recently been used in comparative analyses of agroecosystems (Rufino *et al*., 2009). Thisapproachis known as ecological network analysis, and Rufino *et al*. (2009)presenteda set of indicators including AMI, A, and Finn's cycling index, for assessment of the diversity and organisation of system components governing N flows and food self-sufficiency in three smallholder crop-livestock systems from Ethiopia, Kenya and Zimbabwe. Farm systems are conceptualised as networks, with the household and the farming activities represented ascompartments and the N flows represented as connections between compartments. In this example, indicators assessing network size, activity, cycling, organisation and diversity of the N flows were compared with indicators of productivity and household food self-sufficiency. This analysis revealed that although the amounts of N cycled were small and similarat all sites, resource use efficiency and dependence on external resources differed widely between these apparently ‘comparable’ agroecosystems. System performance was positively related to N flow network size, organisation and N cycling, consistent with the hypothesis that increasing the organisation of resource cycling within resource-limited agroecosystems may render these systems more adaptable and less vulnerable.

The main hypothesis underlyingthe use of these indicators is that agroecosystems retain the properties of the natural ecosystems for which these indices were derived. Ulanowicz (2004) calculated the value of several indicators of network size and organisation, such as the number of different nodes and flows, their roles and their connectivity, for a number of natural ecosystems and agroecosystems. This exercise revealed wider gaps between these systems in terms of indicators of organisation than for the magnitude of energy matter and information flow within them. In other words, increasing organisation makes it possible to do much more with the same resources, while contributing to system stability. The extent and the manner in which organisation contributes to building resilience in agroecosystems is a fascinating research area that remains largely unexplored. Existing frameworks of thinking about resilience in the field of ecology and nature conservation may also be of interest here (e.g., Walker *et al*., 2010). An indirect measurement of the organisation of an agroecosystem is its energy and entropy balance. Svirezhev (2000) proposed the use of thermodynamics concepts to assess the sustainability of agroecosystems, based on the principle that an ecosystem in equilibrium with its environment has a certain 'capacity' to absorb anthropogenic stress that is regulated by its capacity to expel entropy back towards the environment (the 'entropy pump'). This capacity, which emerges from variousagroecosystem properties, can be used to characterise the status of an agroecosystem with respect to the adjacent natural ecosystem from which it has been derived.

Manyof the properties of agroecosystems are often interdependent, together determining thevulnerability and adaptation capacity of these systems in the face of external shocks and stressors (Luers, 2005). Far from being postulates of a new theory, these properties are discussed here as operational, working concepts. We know that the provision of agroecosystem service functions is regulated by the intrinsic properties of these systems, thefunctionality of which can be influenced by design. In practical terms, 'design' implies proposing alternative configurations for the organisation of energy, matter and information flows towards, within and from the system in space and time. The examples examined here indicate that, up to a certain critical level, an increase in the diversity of system components and interrelationships confers desirable properties onagroecosystems consistent with the paradigm of ecological intensification. However, these properties manifest themselves as patterns in space and time that become more evident at particular scales and are often described as variability and/or heterogeneity at other scales. Diversity and spatio-temporal variability or heterogeneity are inherent to agroecosystems (Burel & Baudry, 2003), and may represent constraints to the representation of these systems in prototyping or modelling, which isoften based on modal agroecosystem configurations.

4 – Overall discussion and conclusion

Wide new avenues seem to be opening up in agronomy to guide ecological intensification. We have tried here to identify new sources of knowledge and methods and to consider their potential role (Figure 1). The analysis, use and optimisation of biological regulation in agroecosystems are the most commonly promoted methods of ecological intensification. This approach frequently involves enlarging the foundations of agronomic knowledgeto cover biotic components of the system and their interactions. This ecological analysis of the whole system is of paramount importance, and further investment in this approach is required.This will involve the expansion of agronomic knowledge through classical avenues of research, involving the generation of data mostlythrough modelling and on-station experiments, and their analysis through simulation studies or statistical hypothesis testing. Our proposed approach is complementary to attempts to increase our understanding of biological regulations in agroecosystems and to use this knowledgefor ecological intensification. Indeed, the extension of sources of knowledge to natural ecosystems and farmers' knowledge relates mostly tobiological regulation and is fundamentally consistent with the scientific approach to acquiring knowledge about biological regulation in agroecosystems. The extension of sources of knowledge to the results of plant sciencesresearch is more debatable. For example, Vanloqueren andBaret (2009) argued that genetic engineering closes off avenues ofagroecological innovation. However, plant science results are not inevitably linked to a single technological regime. Agronomists, if they were aware of current knowledge in plant sciences, could make use of some of this knowledge to rebalance technological regimes or to construct new ones.The expansion of sources of knowledge will also indirectly promote ways of generating data that are little used at the moment. Most agronomic data are still acquired through on-station trials and modelling. The extension of sources of knowledge to farmers' knowledge and natural ecosystems will highlightalternative methodsof data generation. This will, in turn, incite the development of new data processing methods, such as meta-analysis and comparative studies.

The new avenues outlined here will require major methodological investment. Indeed, the extension of sources of knowledge suggested here is far from straightforward. Plant science results must be thoroughly screened by groups of agronomists and plant scientists working together, to identify the most promising results for use in ecological intensification. Three major points should be made:

(i) Most plant science knowledge of potential use in agronomy is based on genetic drivers. As gene expression depends on environmental conditions, the use ofplant science data in ecological intensification will require qualification and quantification of the corresponding genotype x environment interactions, for a range of cropping systems, soils and climatic conditions (see for example Spiertz *et al*., 2007).

(ii) All dimensions of cropping system management may benefit from a greater knowledge of plant biologyand soil ecology: crop rotation sequences, soil management, crop management etc.Furthermore, most of the issues raised by ecological intensification can be addressed: yield increase, cut-off forthe use of limited resources through better mineral use efficiency, decrease in pesticide use through the adoption of new crop protection methods, etc.

(iii) Our paper is limited to afew examples. To our knowledge, probably due to schism betweenagronomists and plant scientists, no formal attempt to enlarge this list has been made by systematically tracking plant science results of potential use in cropping system design. Such tracking of results and the publication of the findings obtained would nonetheless be of considerable interest.

The use of knowledge relating to natural ecosystems requires clarification concerning what to study and how, for each of the properties of agroecosystems that ecological intensification aims to improve. This suggests a possible step-wise course of action for agronomists seeking to mimic natural ecosystems:

- Selection of the functions agronomists wish to improve (for example, nutrient cycle management);
- Identification, in natural ecosystems, of the structural characteristics (spatial heterogeneity, diversification of vegetation strata, variability of species in time and space, etc.) modifying these functions;
- Definition of the qualitative or quantitative relationships linking properties and functions;
- Transposition of these functions toagricultural conditions;
- Use of these functions for the design ofagroecosystems with specified aims;

- Checkingthat the new agroecosystems express the targeted functions and have noundesirableproperties.

This procedure seems far more complex than simply trying to design agroecosystems “as similar as possible” to natural ecosystems.

Farmers’ knowledge seems to be extremely valuable, and its use in association with scientific knowledge requires appropriate processing by methods that are not yet well established. Specific methods remain to be adapted from other domains or developed. The first methodological requirement is a more profound analysis of local knowledge to determinewhich processes (ecological or otherwise) should beselected and how they can beused or manipulated. Davis andRuddle (2010) analysed the ways in whichecological knowledge (local, traditional or indigenous) is used and concluded that the same level of scrutiny as for scientific experimental results should be applied before such knowledge is accepted. However, this local knowledge is built within specific ‘systems of knowledge’ (Davis & Ruddle, 2010), and thereforecannot be analysed purely in terms of its content relevant to agronomy or ecological science. It must also be analysed from a social point of view (which processes lead to this knowledge? How is it shared, transmitted etc.?). This analysis calls for pluridisciplinary approaches. We also need to design approaches inspired by or directly making use of the argumentation theory and methods developed in the domain of artificial intelligence (Amgoud & Prade, 2009).

The use of meta-analysis methods for ecological intensification benefits from extensive experience in other research areas, and follows guidelines that have proved to be effective. Nevertheless, data acquisition in agronomy has not traditionally been organised with the requirements of subsequent meta-analyses in mind. As a consequence, considerable effort is required to adapt the methods to existing agronomic data and to establish guidelines for the generation of further data. Finally, comparative studies in agriculture often remain descriptive, and are not always oriented to identify the relationships between agroecosystem structure and functioning—undoubtedly a new challenge for agronomic research.Addressing this aim will require the development of guidelines for site selection, characterisation methods, data processing, etc.

Finally, each of the five topics outlined will probably require specific organisation within research institutes. They may also induce changes in academic curricula in agronomy, as plant scientists and agronomists currently follow different curricula, with little in the way of shared knowledge, concepts and technical skills.

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Figure captions

Figure 1. Summary of new avenues ofagronomic research for ecological intensification

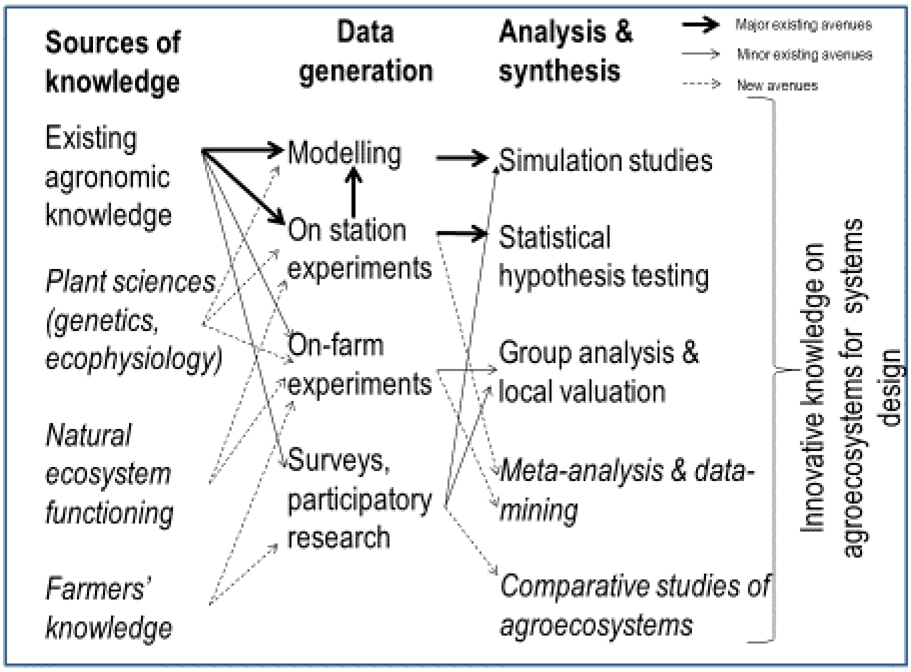
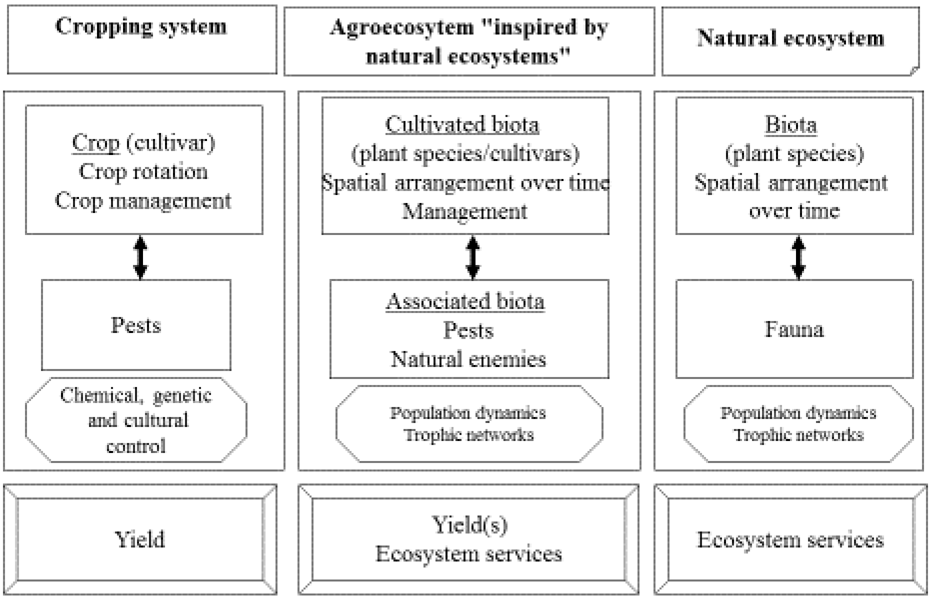

Sources of knowledge
Data generation
Analysis & synthesis
Major existing avenues
Minor existing avenues
New avenues
Existing agronomic knowledge
Plant sciences (genetics, ecophysiology)
Natural ecosystem functioning
Farmers' knowledge
Modelling
On station experiments
On-farm experiments
Surveys, participatory research
Simulation studies
Statistical hypothesis testing
Group analysis & local valuation
Meta-analysis & data-mining
Comparative studies of agroecosystems
Innovative knowledge on agroecosystems for systems design

Figure 2. A comparison of natural ecosystems, conventional cropping systems and agroecosystems inspired from natural ecosystems, with an emphasis on crop protection



Tables

Table 1. Examples of recent results fromplant sciences useful in agronomy

Topics inplant sciences	**Key references**	**Potential agronomic benefits**
Plant architecture	Zhu *et al*. (2010) Walter *et al*. (2009) dePury& Farquhar (1997)	Increased radiation interception
Photosynthesis efficiency	Wang & Li (2008)	Canopy pattern target for crop management Increase in yield Identification of genotypes adapted for crop mixture
Exchanges of nitrogen between roots and environment	Jackson *et al*. 2008	Improved fertiliser use efficiency
Role of organic anion exudation	Glass (2003) Ryan *et al.* (2001)	Improved nitrogen management
Interaction between roots and soil organisms	Mehboob *et al*. (2009) Brussaard et al. (2007)	Improved mineral nutrition
Role of common mycorrhizal networks	Micallef *et al.* (2009) Ryan *et al.* (2009) Sturz and Nowak (2000) Van der Heijden & Horton (2009)	Improved crop growth Adaptation of crop management
Interaction between aerial parts of the plant and environment	De Bruxelles & Roberts (2001)	Management of natural defences for improved resistance to pests

Table 2. Examples of farmers' knowledge potentially useful in agronomy

Sources of knowledge	**Key references**	**Potential agronomic benefit**
Local ecological knowledge	Chalmers & Fabricius (2007)	Explaining changes in agricultural systems
Traditional farming systems	Singh & Sureja (2007)	Design of sustainable farming systems
	Abbona *et al*. (2007)	Understanding of ecological processes
Local knowledge and indicators for assessing forest management	Ballard *et al.* (2008)	Assessment of management practices for forests
Farmer's indicators supporting decision making	Tchamitchian *et al*. (2006)	Indicators with expanded domains of validity

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